



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Interpolating between head-related transfer functions measured with low directional resolution

Christensen, Flemming; Møller, Henrik; Minnaar, Pauli; Plogsties, Jan; Olesen, Søren Krarup

Published in:

Proceedings of 107th Audio Engineering Society Convention, September 24-27, 1999, New York, USA

Publication date:

1999

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Christensen, F., Møller, H., Minnaar, P., Plogsties, J., & Olesen, S. K. (1999). Interpolating between head-related transfer functions measured with low directional resolution. In *Proceedings of 107th Audio Engineering Society Convention, September 24-27, 1999, New York, USA*

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Flemming Christensen, Henrik Møller, Pauli Minnaar, Jan Plogsties, and Søren Krarup Olesen
Aalborg University
DK-9220 Aalborg, Denmark

**Presented at
the 107th Convention
1999 September 24-27
New York**



AES

This preprint has been reproduced from the author's advance manuscript, without editing, corrections or consideration by the Review Board. The AES takes no responsibility for the contents.

Additional preprints may be obtained by sending request and remittance to the Audio Engineering Society, 60 East 42nd St., New York, New York 10165-2520, USA.

All rights reserved. Reproduction of this preprint, or any portion thereof, is not permitted without direct permission from the Journal of the Audio Engineering Society.

AN AUDIO ENGINEERING SOCIETY PREPRINT

Interpolating between head-related transfer functions measured with low directional resolution

Flemming Christensen, Henrik Møller, Pauli Minnaar,
Jan Plogsties and Søren Krarup Olesen

Acoustics Laboratory, Aalborg University
Fredrik Bajers Vej 7 B4, DK-9220 Aalborg Ø, Denmark
acoustics@kom.auc.dk

Abstract

Head-related transfer functions used in binaural synthesis are usually measured with low directional resolution. Intermediate transfer functions are found by interpolation. In this study measurements with a high directional resolution are used to determine the lowest resolution needed to interpolate head-related transfer functions precisely. The measured and interpolated head-related transfer functions are compared in an objective analysis and a listening experiment.

1 Introduction

In binaural synthesis head-related transfer functions (HRTFs) are used which should in principle represent every possible direction relative to a listener. Since it is not possible to measure HRTFs for all directions around the listener measurements are made with a finite, and often low, directional resolution. It is desired to minimise the number of directional filters stored in a binaural synthesis system. Therefore, filters between those, derived from measurements, have to be constructed. This calls for interpolation between the measured directional filters: either off-line or at real-time.

In the present investigation HRTFs are measured with a high directional resolution. Interpolations made from subsets of the measurements are compared to measurements from the target directions. The error is determined when interpolating from a given directional resolution. Furthermore the needed resolution is determined for a given error. The difference between the measured and interpolated HRTFs is inspected by means of 1) data analysis and 2) a listening experiment.

It should be clear that the directional resolution needed during measurements depends directly on the interpolation strategy used. The HRTF measurements are interpolated here by linear interpolation of the aligned impulse responses. This fast and simple method is investigated since it is well established and finds wide application.

2 Previous work

A large number of HRTF measurements are reported in the literature. Some measurements were used for analytical purposes and cover only a few directions, whereas some cover the whole sphere around the head and can be used in binaural synthesis. A list of studies on HRTF measurements is found in Møller et al. [1].

Different interpolation strategies can be used to find HRTFs between measurements. The strategies described in previous investigations arise from different ways of representing HRTFs, e.g. in the time or frequency domains or as pole-zero models. Linear interpolation of the impulse responses of measured HRTFs has been applied in various studies and implementations, especially when interpolating in real-time. Sandvad [2] used the weighted average of time-domain points of neighbouring HRTFs. The effect of linear time domain interpolation of HRTFs on localisation was investigated by Wenzel and Foster [3]. Measured HRTFs and the minimum-phase components of those were compared to interpolated HRTFs for different interpolation intervals.

Hartung et al. [4] compared two interpolation methods applied to both time domain and frequency domain representation of HRTFs: inverse-distance weighting and spherical splines. Unlike most other 'local' interpolation methods, spherical spline interpolation works on the HRTF data from the entire sphere to calculate the HRTF of a certain direction. Spatial frequency response surfaces (SFRSs) as spatial domain representations of HRTFs were proposed by Cheng and Wakefield [5]. An SFRS represents the magnitudes of all HRTFs of a certain frequency bin; i.e. SFRS are functions of azimuth and elevation. On each SFRS (for each frequency bin) the magnitude value of the target direction is then calculated as the weighted average of the neighbouring values.

Another approach originates from the pole-zero modelling of HRTFs. In a study by Runkle et al. [6] the interpolation of the poles and zeros is performed linearly and along tracks of poles and zeros found by a gradient search algorithm. Other methods of interpolation arising from pole-zero description of HRTFs are reviewed by Jot. et al. [7].

A functional representation of HRTFs obtained by e.g. principal components analysis (PCA) [8] or spatial feature extraction and regularisation (SFER) [9] result in further methods of interpolating HRTFs between measured directions.

3 Measurement procedure

If high-resolution measurements are made on a human being, head movements can exceed the measurement angle resolution and thus corrupt the measurements. Therefore, the artificial head, VALDEMAR, was used for measurement. VALDEMAR was developed at the Acoustics Laboratory at Aalborg University and is an approximation of a typical human with head, torso and impressions of human ears. The head was tested in listening experiments and provides good localisation compared to other artificial heads [10], [11].

A polar co-ordinate system is used with poles above and below the head. Horizontal planes are indexed by the azimuth angle where 0 degrees is in front, 90 degrees is on the left, -90 degrees is on the right and 180 degrees is behind the head. Elevation angles are relative to the horizontal plane, i.e. 0 degrees is the horizontal plane, 90 degrees is above and -90 degrees is below the head. Measurements of the HRTFs were made through 360 degrees on four planes through the sphere. They are the horizontal plane (dividing top and bottom), frontal plane (dividing front and back), median plane (dividing left and right) and elevation 45 degrees (a horizontal plane). The measured planes are illustrated in Figure 1.

The artificial head was mounted on a stand that can be rotated in 2-degree steps while the loudspeaker was stationary. The artificial head can be mounted in a vertical as well as a horizontal position. When measuring the horizontal plane, the artificial head was mounted vertically as shown in Figure 2a and the sound source was positioned on the level of the ear canals. For the median plane measurement the head was mounted horizontally as shown in Figure 2b. For the frontal plane, the head was again mounted horizontally but with the nose pointing upwards. In these three cases the centre of the head was the rotational centre while the distance to the loudspeaker was 2.2 metres. For the measurement of the 45 degrees elevated plane, the loudspeaker was positioned at 45 degrees elevation at a distance of 2 metres.

The measurements were made at the entrance to the blocked ear canals using small microphones (Sennheiser KE4-211-2) mounted in foam earplugs. A 2-channel maximum length sequence measurement system was used to acquire the impulse responses from the measurement directions. A measurement at a reference point at the centre of the head with the head absent was deconvolved from the directional measurements in order to obtain the HRTFs. For a more thorough description of the measurement technique and microphone placement see Møller et al. [1] and Møller [12].

4 Objective evaluation

In this section the measurements made at 2 degrees resolution are shown for the four planes for frequencies between 100 Hz and 20 kHz. The magnitude of the HRTFs is shown (in dB) for the left ear of VALDEMAR. The error made during interpolation is evaluated as the difference between magnitudes of the interpolated and measured HRTFs. In this work the interaural time difference and specific phase structure of the HRTFs are not considered.

4.1 Measurements on the four planes

The HRTFs in the horizontal plane are shown in Figure 3a. Notice that the upper part of the figure is for the ipsilateral side whereas the bottom of the figure corresponds to when the sound source is on the contralateral side of the head. The structure on the ipsilateral side appears to be less ‘complicated’ than the contralateral side. The interference of sound waves that arises from the different paths around the head to the contralateral ear is particularly clear. Distinct ‘valleys’ are seen on the contralateral side that extend to frequencies as low as 1 kHz. When a single HRTF is inspected these valleys are seen as dips at regular frequency intervals as for a typical comb filter.

Figure 3b shows the magnitude of the HRTFs in the frontal plane. The top of the figure corresponds to the left (ipsilateral) side of the head and the bottom part is on the right (contralateral) side. The level is relatively low at high frequencies below the horizontal plane on the contralateral side. Shallow peaks and valleys, repeating at regular intervals, are seen between 0 degrees on the ipsilateral side and 45 degrees on the contralateral side. This is also the angular region within which the torso reflection (shoulders) is expected to be seen as a systematically changing comb filter. In the time domain (not shown) the shoulder reflection is seen about 1 ms after the ‘direct sound’ for 90 degrees elevation. This corresponds to a path length difference of approximately 33 cm, which is twice the distance between the shoulder and the pinna. The comb filter expected from a 1 ms delay has dips at 1 kHz intervals, which is indeed clear at 90 degrees elevation.

Figure 3c shows the magnitude of the HRTFs in the median plane. The top of the figure corresponds to the direction in front of the head whereas the bottom part is behind. The same torso reflection as for the frontal plane is seen here from -45 degrees in front to -45 degrees behind. A certain asymmetry between the front and the back is noticed especially for frequencies above about 7 kHz.

The magnitude of the HRTFs in the horizontal plane at an elevation of 45 degrees is shown in Figure 3d. Compared to the three planes in Figures 3a, 3b and 3c the magnitude changes slowly with angle. Although the differences between the HRTFs are small it is worth remembering that the measurements become increasingly closer to each other as the elevation increases.

4.2 Interpolating from different resolutions

In order to investigate the errors made during interpolation the HRTF set measured with 2 degrees resolution is used as reference. Subsets of HRTFs with a lower angular resolution are extracted from the reference set. The resolution here refers to the angular difference (in degrees) between measurements. The HRTFs for angles between the measurements are found by interpolating the time functions (impulse responses). The minimum phase component is found for every HRTF, which conveniently aligns the impulse responses. The measurements are then interpolated to 2 degrees resolution by linear interpolation of the impulse responses. The error is evaluated as the absolute magnitude difference (in dB) between the measured and the interpolated HRTFs at each frequency.

Figure 4a shows the magnitude error between the measured and the interpolated sets of HRTFs for the horizontal plane. The colour becomes darker as the error increases up to 6 dB after which the error is indicated in black. It is clear that the errors are 0 dB on the angular position corresponding to the chosen resolution, whereas the largest errors tend to be in the middle of the interval. The largest errors are made on the contralateral side for all resolutions shown. On the other hand errors are mainly above about 8 kHz for the ipsilateral side. Errors are still seen even for a resolution as high as 4 degrees.

In the frontal plane, shown in Figure 4b, the ipsilateral side is again seen to be less prone to errors than the contralateral side. As for the horizontal plane errors are still seen on the contralateral side even at 4 degrees resolution. It is interesting that the errors are relatively small above the head, especially in the elevation range of 45 to 90 degrees.

The errors in the median plane, Figure 4c, are comparable to those in Figure 4b in terms of the small errors above 45 degrees elevation. More errors are seen in front than behind the head. As is the case for the frontal plane, the large errors found for directions beneath the torso may not be of great practical importance.

Figure 4d shows the magnitude error between the measured and the interpolated set of HRTFs for the plane at 45 degrees elevation. The errors are strikingly small and even for a resolution as coarse as 24 degrees errors are only found above 10 kHz. This ties in well with the observations made from the frontal and median planes about the errors for elevations of 45 degrees and above. The errors in this plane are small because 1) measurements are physically close to each other, 2) the magnitude changes smoothly with the azimuth and 3) deep valleys are not seen in the measurements (as is the case for the other 3 planes).

4.3 The needed resolution

Figures 4a to 4d showed the error in the magnitude if measurements at a given resolution were used. No error was made when the interpolated direction corresponded to a direction of a measurement. Therefore, Figures 4a to 4d would change slightly if angular offset was introduced to the measurement positions for a given resolution. In Figures 5a to 5d this is addressed by calculating the error for a given direction by ensuring that it always is in the middle of the interpolation interval. It may be seen as a 'worst case' calculation for every direction. As an example for 20 degrees resolution at 92 degrees azimuth the interpolation would be done between measurements at 82 and 102 degrees.

For a given resolution the error between the measured and interpolated sets of HRTFs is evaluated, frequency by frequency, and if the error is above 3 dB it is given a colour. This is done by stepping through from low (36 degrees) to high (4 degrees) resolution. The certain colour in the figure therefore corresponds to the resolution range found on the scale for which the error is below 3 dB.

Figure 5a shows the resolution needed to ensure that the absolute error between measurements and interpolations at a given frequency is below 3 dB in the horizontal plane. As in Figure 4a the most errors are on the contralateral side between -45 and -135 degrees azimuth. For most of the rest of the plane below 7 kHz the errors are below 3 dB even for 36 degrees resolution. It is clear when comparing Figure 5a to Figure 3a that the errors occur where the local change in the magnitude is high. So the errors seen where neighbouring deep valleys and tall peaks are found in the measurements.

The absolute error in the magnitude is shown for the frontal and the median plane in Figures 5b and 5c respectively. The error is less than 3 dB for a large part of the frontal and median planes when interpolated from measurements at 20 degrees resolution. In both plots errors are seen for sound coming from below the head. Here the comb filters (valleys) due to the multiple paths of the sound would be slightly different if legs were present or if the manikin was 'seated'.

The errors seen in Figure 5d are for the plane at elevation 45 degrees. As expected the errors are relatively small. Even for this 'worst case' calculation the errors are below 3 dB for frequencies up to 10 kHz even for interpolations made from measurements at 36 degrees resolution.

5 Subjective evaluation

A subjective experiment is planned in which a group of people will participate in a three-alternative forced choice listening test. In the experiment three consecutive sounds, each filtered with either the measured or interpolated HRTFs, will be presented through headphones. The listening test along with the results will be presented at the convention.

6 Summary

HRTF measurements were made with a resolution of 2 degrees on the artificial head VALDEMAR. From these HRTFs subsets were extracted and interpolated to obtain sets with the same angular resolution. The magnitude of an interpolated HRTF was compared to that of a measurement for each specific direction. The angular resolution needed in measurements was seen to depend on the HRTF azimuth and elevation.

An objective analysis showed that the errors made during interpolation are larger on the contralateral than the ipsilateral side of the head. This is due to the structure of the contralateral HRTFs that contains many narrow dips. Figure 6 shows the magnitude for the 90 and -90 degrees azimuth in the horizontal plane together with interpolations made from 20 degrees resolution (as seen in Figure 4a). Although the errors are larger on the contralateral side the interaural level difference is also very large, especially at high frequencies. Therefore, the exact structure of the HRTFs may be less important on the contralateral than the ipsilateral side. An investigation by Wightman and Kistler [13] suggests that the degradation of the spectrum on the contralateral side has only a minor effect on localisation. The planned listening test should shed more light on the importance of the error on the contralateral side.

The angular resolution needed for making successful interpolations will depend on the specific interpolation strategy used. In this study the impulse responses of the minimum phase components of the HRTFs were linearly interpolated. This method has practical appeal since it is relatively simple and can be used for either off-line or real time interpolation.

A conclusion on the angular resolution needed for HRTF measurements will be drawn once the listening experiment is completed. However, it is seen from the objective analysis that there is little difference between the measured and interpolated HRTFs for directions above the head. This suggests that for elevations larger than 45 degrees only few measurements are needed.

7 Acknowledgement

We want to thank M. Sc. graduate students Bjarke Pihl Bovbjerg and Jacob Florian Randbæk for spending the time to measure this revealing set of HRTFs. Thank you Claus Vestergaard Skipper for the competent assistance in the laboratory. This work was funded by the Danish National Centre for IT Research.

8 References

- [1] H. Møller, M. F. Sørensen, D. Hammershøi, C. B. Jensen, "Head-related transfer functions of human subjects", *J. Audio Eng. Soc.*, Vol. 43, No. 5, pp. 300-321, May 1995.
- [2] J. Sandvad: "Dynamic aspects of auditory virtual environments", *Presented at the 100th Convention of the Audio Engineering Society*, Copenhagen, preprint 4226, 1996.
- [3] E. M. Wenzel, S. H. Foster: "Perceptual consequences of interpolating head-related transfer functions during spatial synthesis" *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, pp. 102-105, 1993.
- [4] K. Hartung, J. Braasch, S. J. Sterbing: "Comparison of different methods for the interpolation of head-related transfer functions", *Presented at the 16th International Conference of the Audio Engineering Society*, Rovaniemi, Finland, pp. 319-329, 1999.
- [5] C. I. Cheng, G. H. Wakefield: "Spatial frequency response surfaces (SFRSs): An alternative visualization and interpolation technique for head-related transfer functions (HRTFs)", *Presented at the 16th International Conference of the Audio Engineering Society*, Rovaniemi, Finland, pp. 147-159, 1999.
- [6] P. R. Runkle, M. A. Blommer, G. H. Wakefield: "A comparison of head-related transfer function interpolation methods", *IEEE ASSP Workshop on Applications of Signal Processing to Audio and Acoustics*, pp. 88-91, 1995.
- [7] J-M. Jot, V. Larcher, O. Warusfel, "Digital signal processing issues in the context of binaural and transaural stereophony", *Presented at the 98th Convention of the Audio Engineering Society*, Paris, France, 1995.
- [8] D. J. Kistler, F. L. Wightman: "A model of head-related transfer functions based on principal components analysis and minimum-phase reconstruction", *J. Acoust. Soc. Am.*, Vol. 91, No. 3, pp. 1637-1647, 1992.
- [9] J. Chen, B. D. Van Veen, K. E. Hecox: "Synthesis of 3D virtual auditory space via a spatial feature extraction and regularization model", *IEEE Virtual Reality Annual International Symposium*, pp.188 -193, 1993.

- [10] P. J. Minnaar, S. K. Olesen, F. Christensen, H. Møller: "Human sound localization with artificial head recordings", *Proceedings of NAM 98*, Nordic Acoustical Meeting, Stockholm, Sweden, September 1998.
- [11] H. Møller, P. J. Minnaar, S. K. Olesen, F. Christensen: "Localisation tests of binaural recording systems", *Presented at the 105th Convention of the Audio Engineering Society*, San Francisco, USA, September 1998. Only abstract available.
- [12] H. Møller: "Fundamentals of binaural technology", *Applied Acoustics*, Vol. 36, No. 3/4, pp. 171-218, 1992.
- [13] F. L. Wightman, D. J. Kistler, "Sound localization with unilaterally degraded spectral cues", *Joint Meeting: 137th Regular Meeting of the Acoustical Society of America, 2nd Convention of the European Acoustics Association, Forum Acusticum 1999, Integrating the 25th German Acoustics DAGA Conference*, Berlin, Germany, March 1999. Abstract in *J. Acoust. Soc. Am.*, Vol. 105, No. 2, Pt. 2, February 1999, (paper 3aSP1).

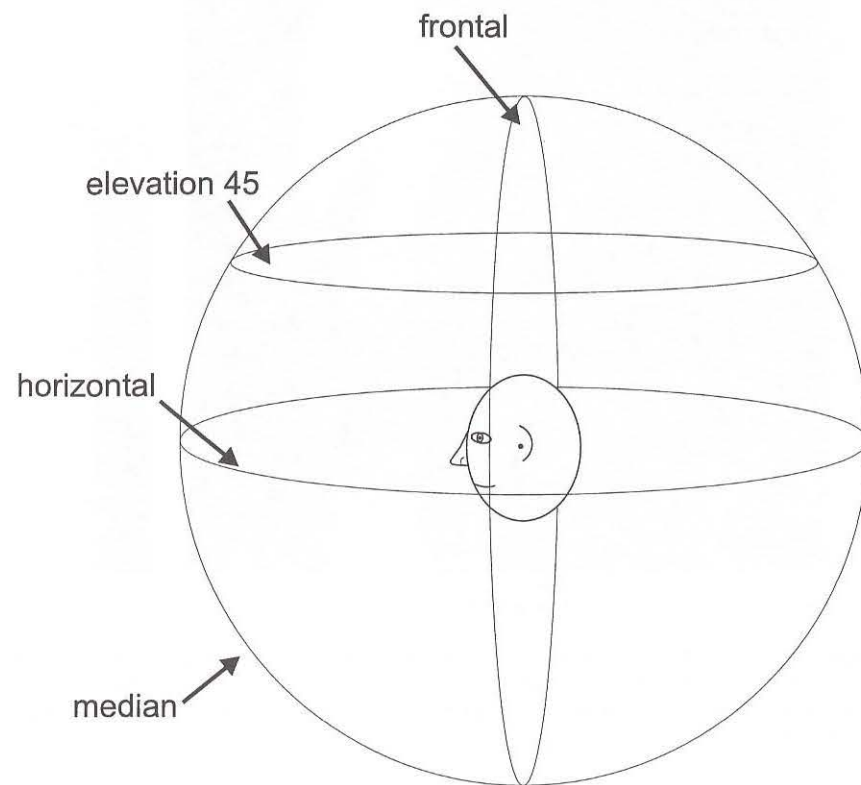


Figure 1. HRTF measurements were made with a loudspeaker on the sphere around the head. The sphere was cut by four planes: the horizontal plane, frontal plane, median plane and the horizontal plane at an elevation of 45 degrees.

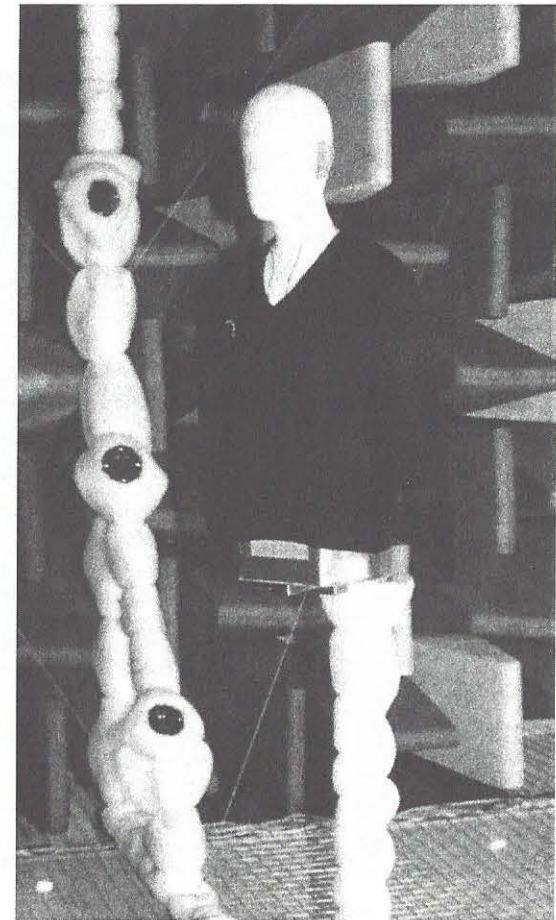


Figure 2a. The artificial head VALDEMAR during horizontal plane HRTF measurements in an anechoic chamber.

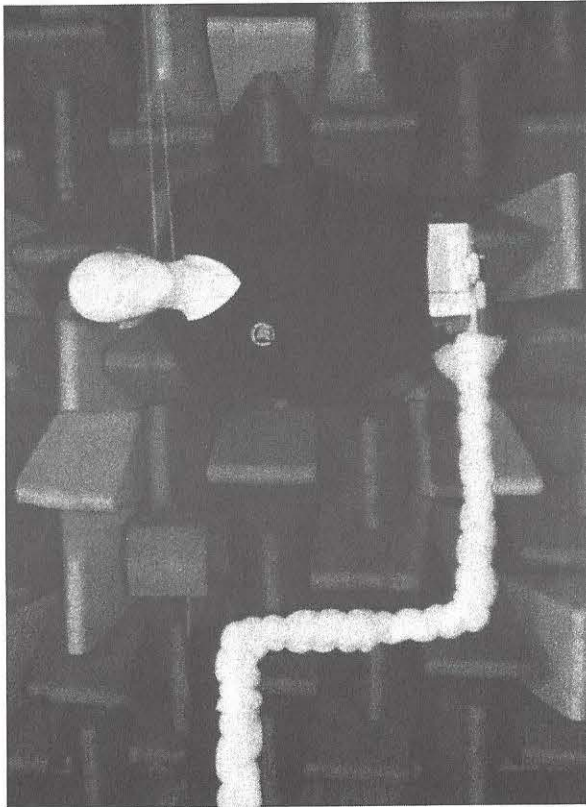


Figure 2b. The artificial head VALDEMAR during median plane HRTF measurements in an anechoic chamber.

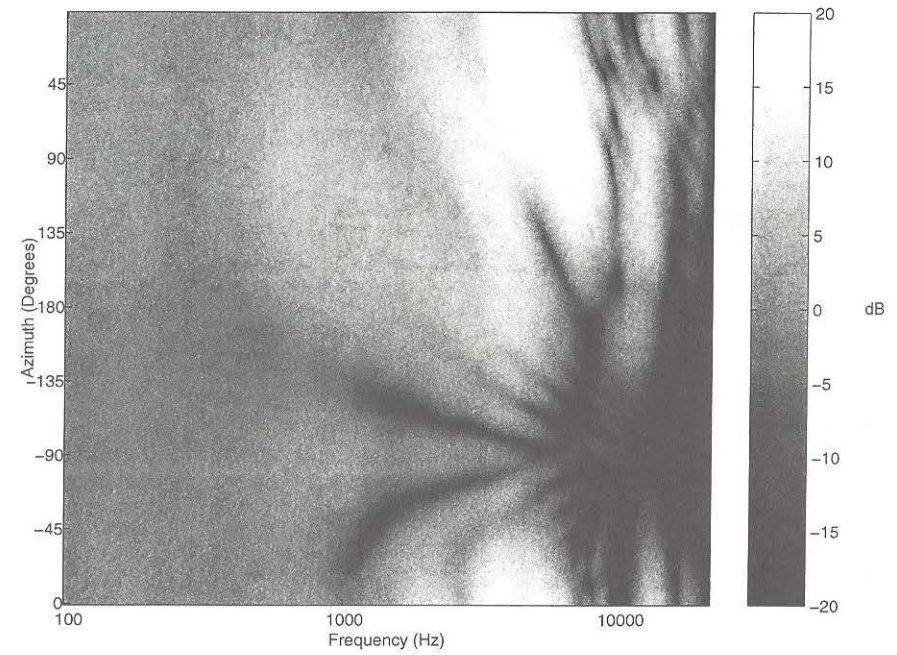


Figure 3a. Horizontal plane: Magnitude of HRTF measurements at 2 degrees resolution for the left ear of VALDEMAR. The azimuth denotes the direction of the sound source: 0 degrees is in front, 180 degrees is behind, 90 degrees is left (ipsilateral) and -90 degrees is right (contralateral).

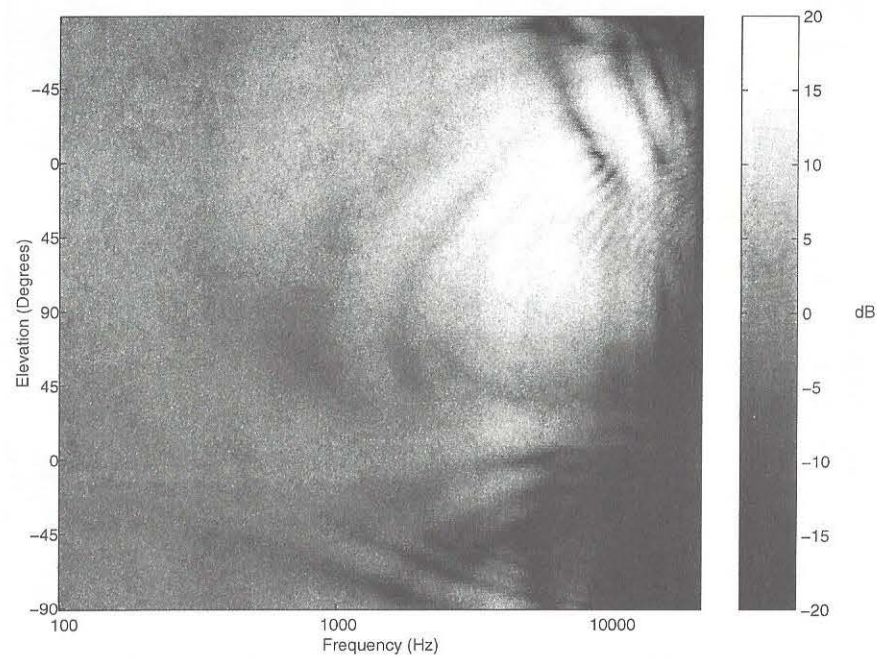


Figure 3b. Frontal plane: Magnitude of HRTF measurements at 2 degrees resolution for the left ear of VALDEMAR. The elevation denotes the direction of the sound source: -90 degrees is below, 0 degrees is in the horizontal plane, 90 degrees is above. Read the figure from top to bottom as: below, left (ipsilateral), above, right (contralateral), below .

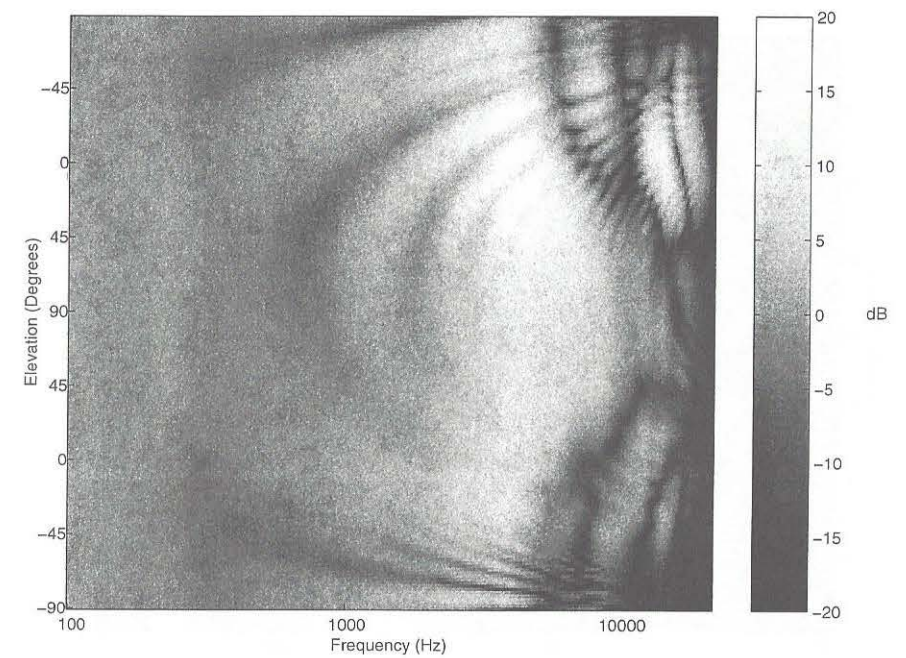


Figure 3c. Median plane: Magnitude of HRTF measurements at 2 degrees resolution for the left ear of VALDEMAR. The elevation denotes the direction of the sound source: -90 degrees is below, 0 degrees is in the horizontal plane, 90 degrees is above. Read the figure from top to bottom as: below, in front, above, behind, below .

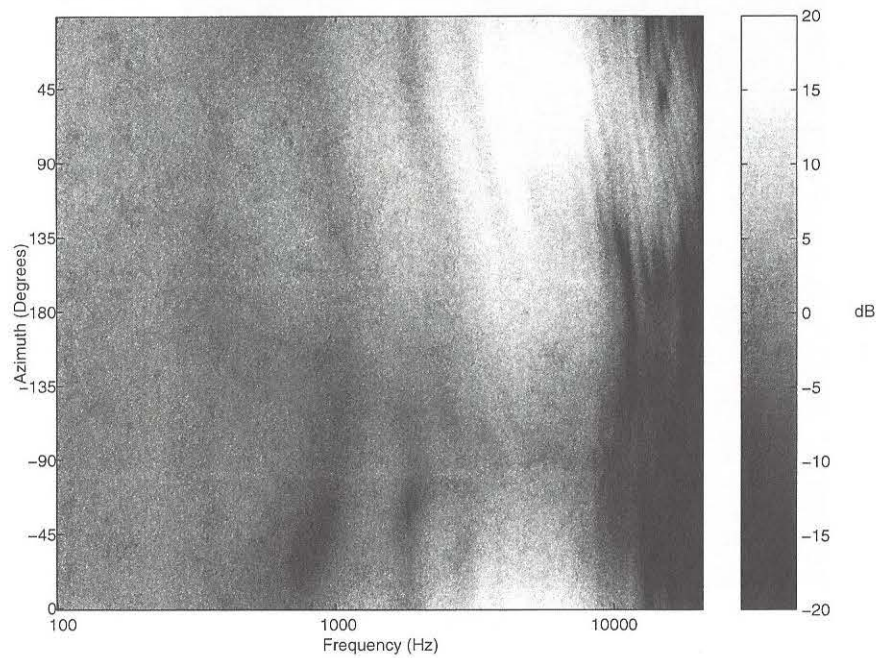


Figure 3d. Elevation 45 degrees: Magnitude of HRTF measurements at 2 degrees resolution for the left ear of VALDEMAR. The azimuth denotes the direction of the sound source: 0 degrees is in front, 180 degrees is behind, 90 degrees is left (ipsilateral) and -90 degrees is right (contralateral).

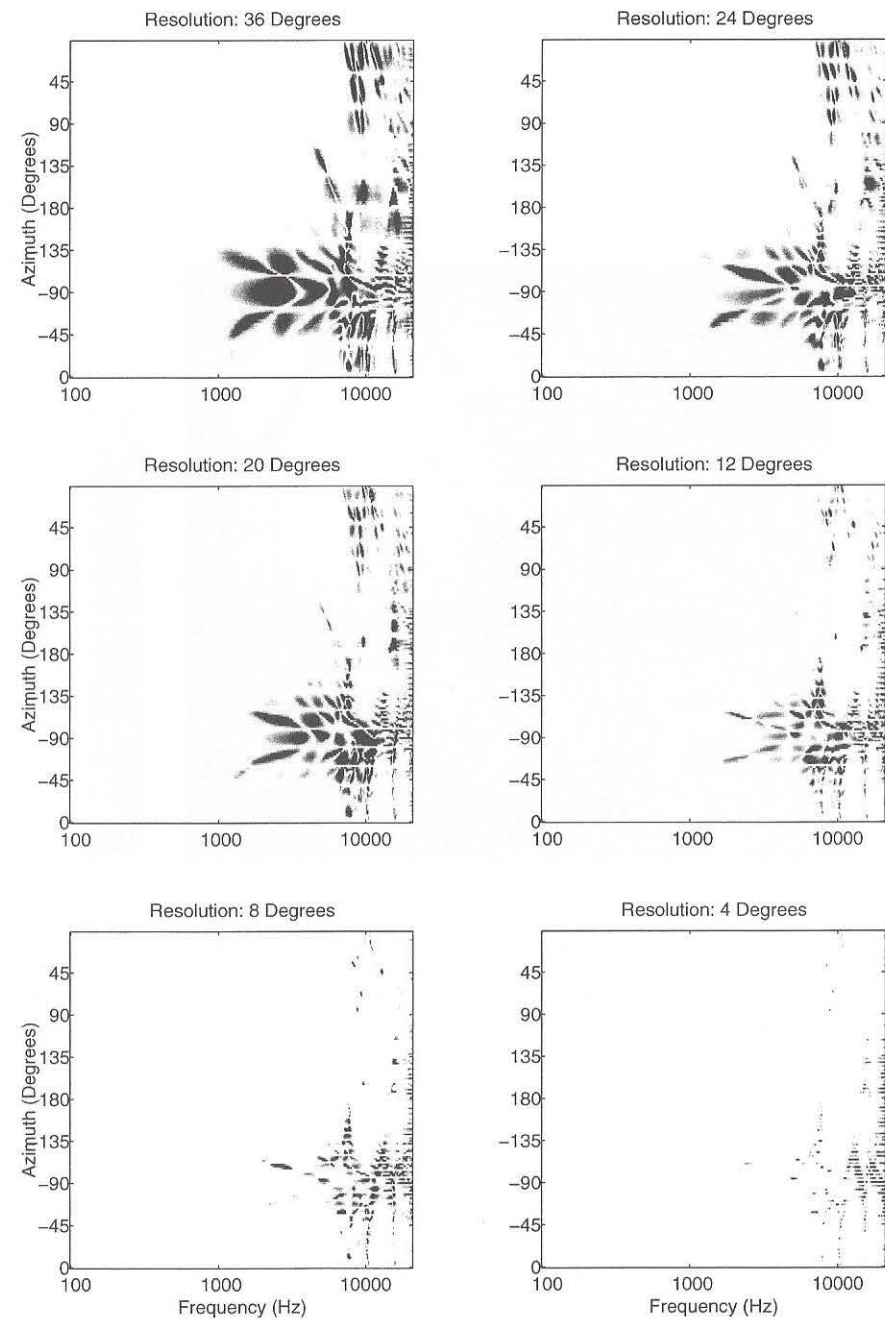


Figure 4a. Horizontal plane: Absolute error between measurements and interpolations for different angular resolutions. Errors above 6 dB are indicated in black.

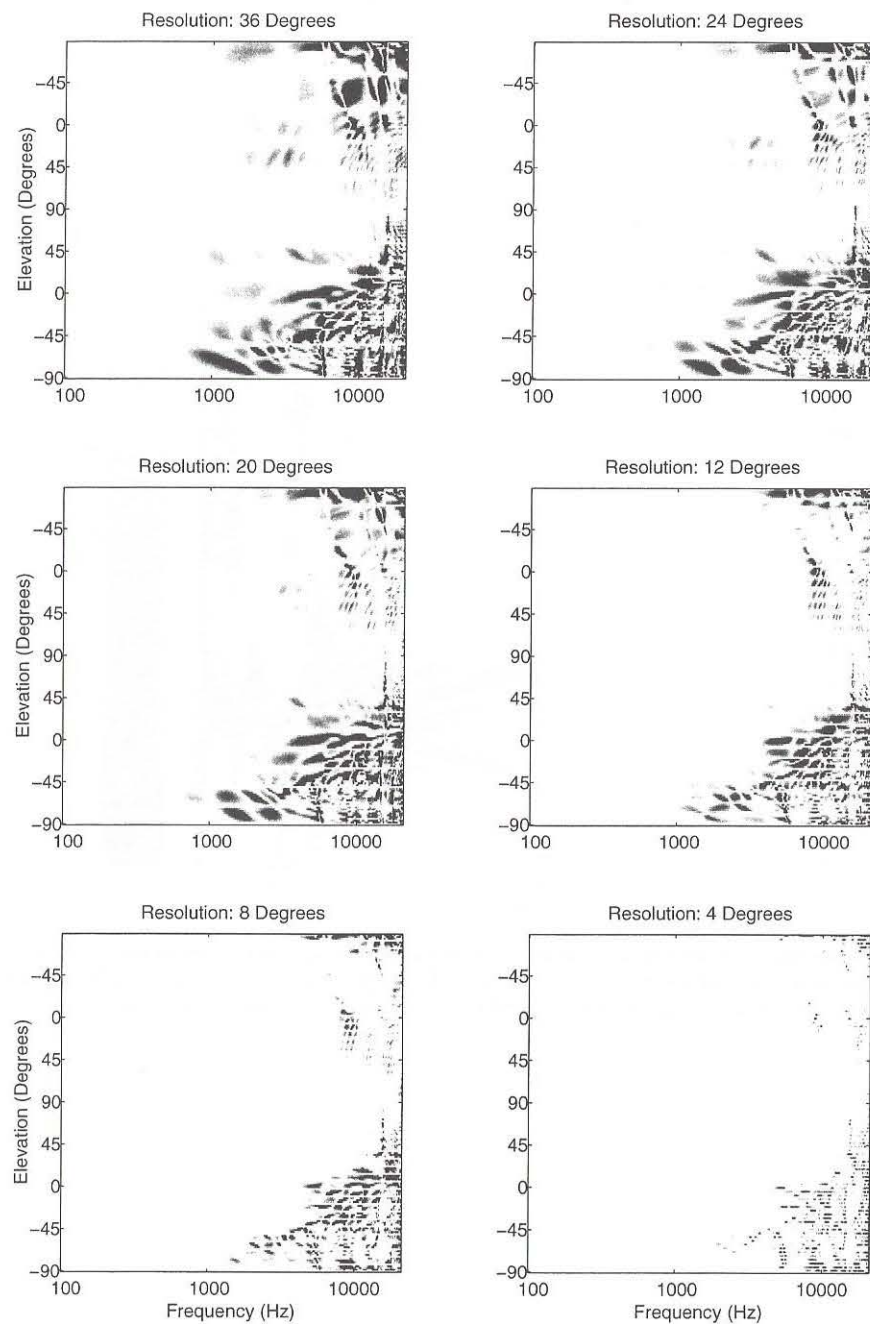


Figure 4b. Frontal plane: Absolute error between measurements and interpolations for different angular resolutions. Errors above 6 dB are indicated in black.

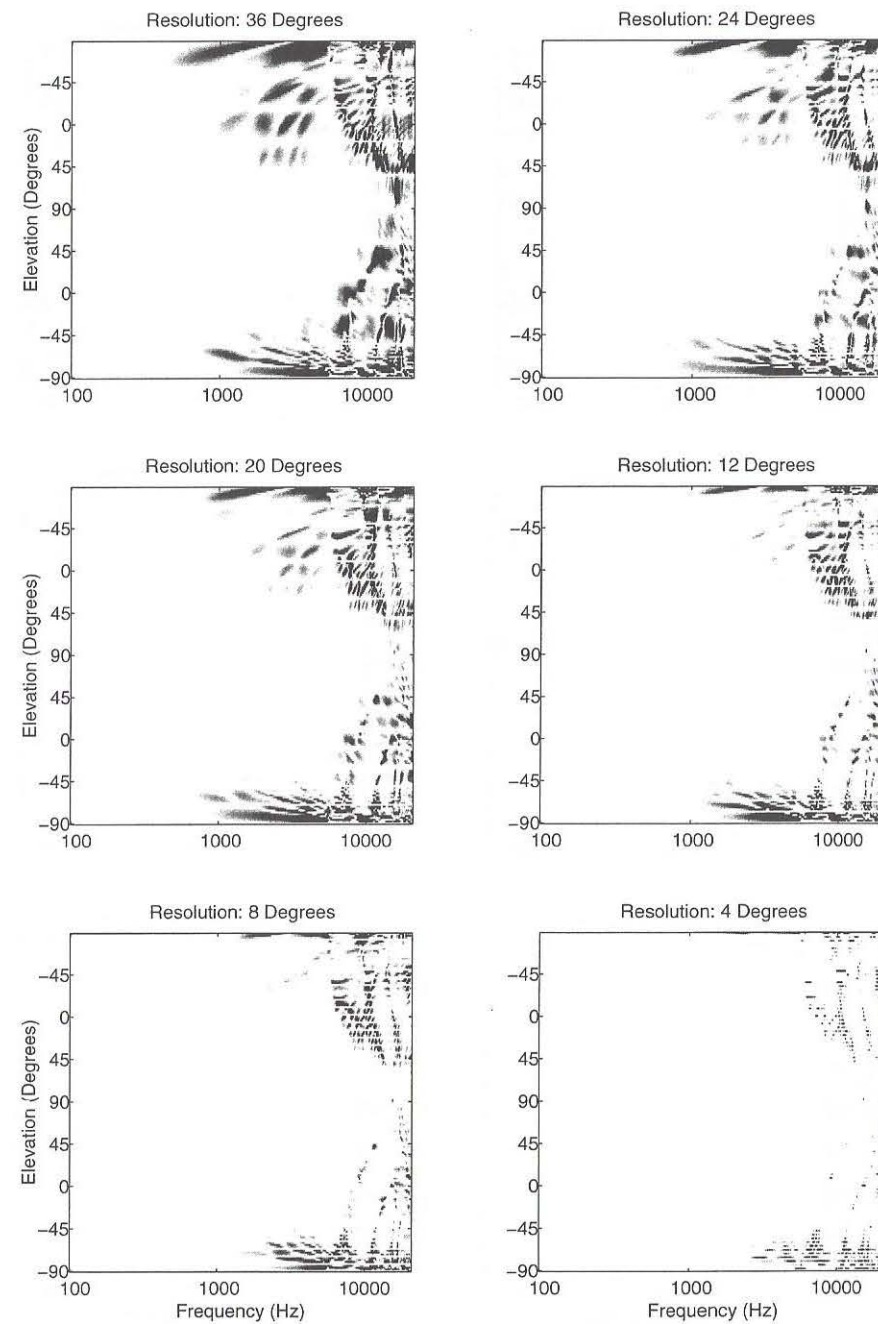


Figure 4c. Median plane: Absolute error between measurements and interpolations for different angular resolutions. Errors above 6 dB are indicated in black.

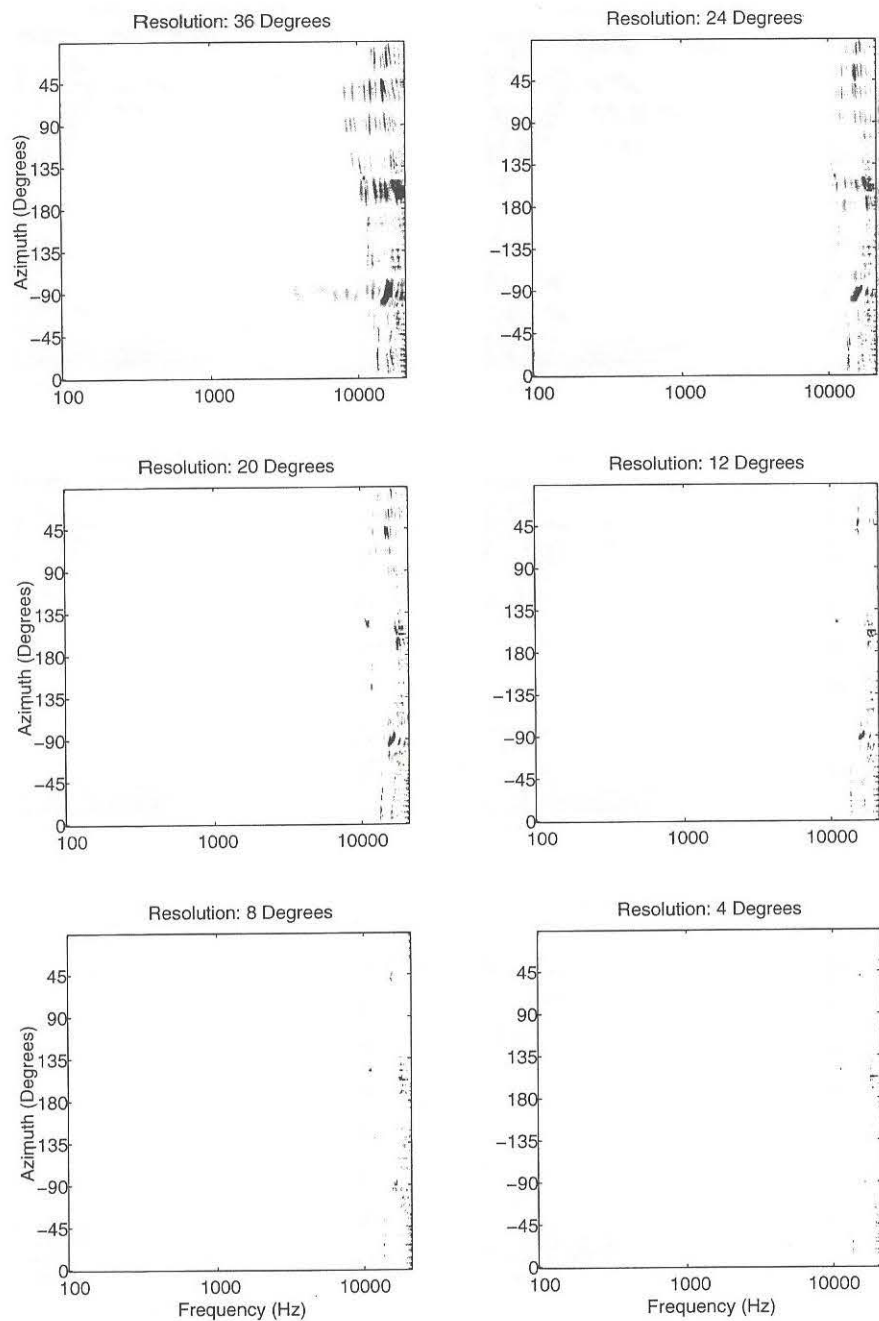


Figure 4d. Elevation 45 degrees: Absolute error between measurements and interpolations for different angular resolutions. Errors above 6 dB are indicated in black.

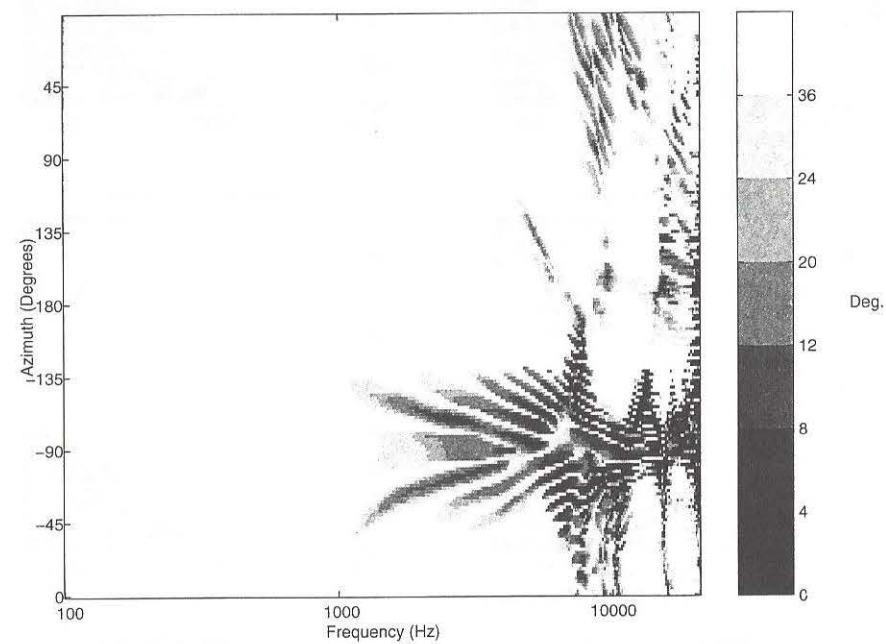


Figure 5a. Horizontal plane: The resolution needed to ensure that the absolute error between measurements and interpolations is below 3 dB. A certain colour in the figure indicates that the error is below 3 dB for the corresponding measurement resolution found on the scale.

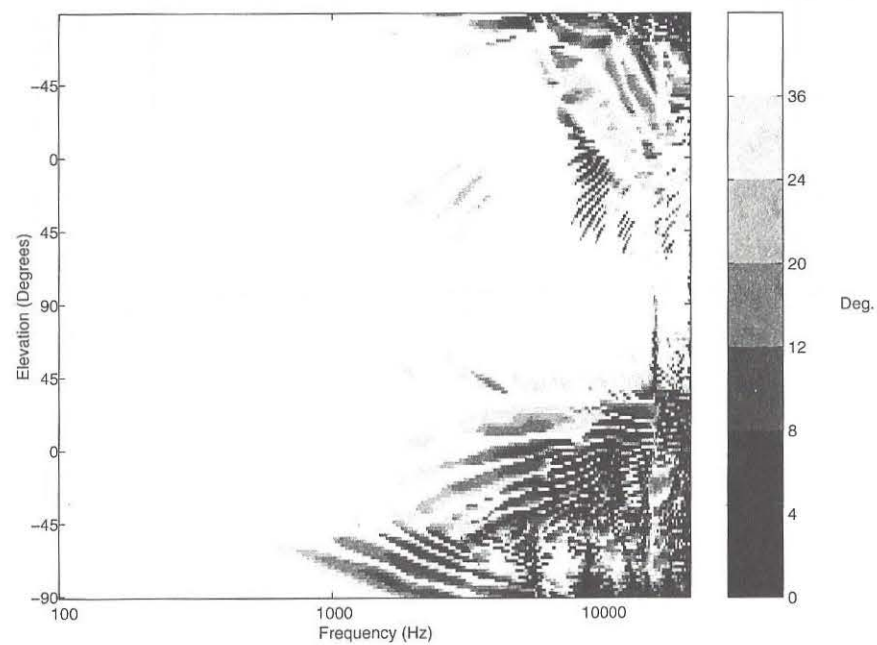


Figure 5b. Frontal plane: The resolution needed to ensure that the absolute error between measurements and interpolations is below 3 dB.

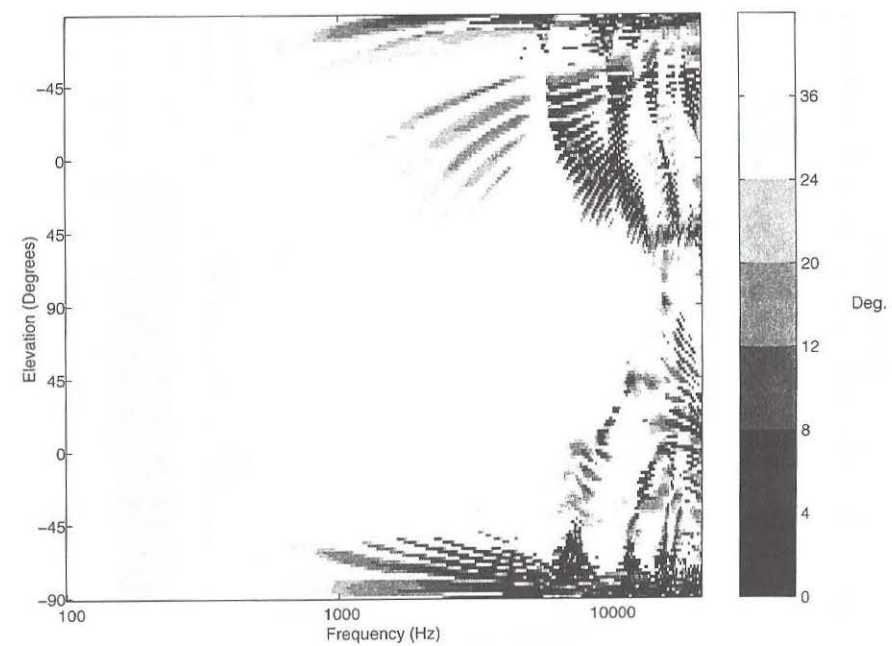


Figure 5c. Median plane: The resolution needed to ensure that the absolute error between measurements and interpolations is below 3 dB.

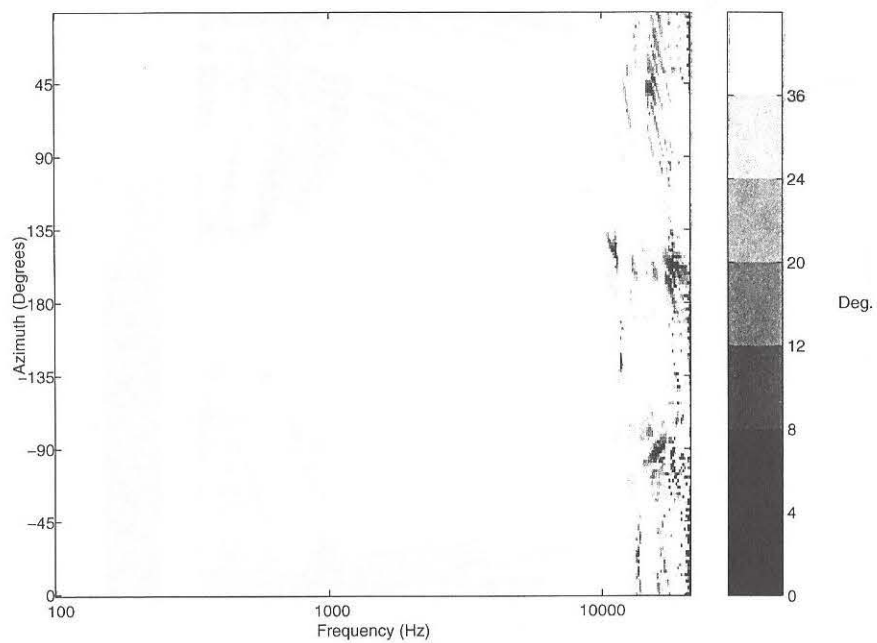


Figure 5d. Elevation 45 degrees: The resolution needed to ensure that the absolute error between measurements and interpolations is below 3 dB.

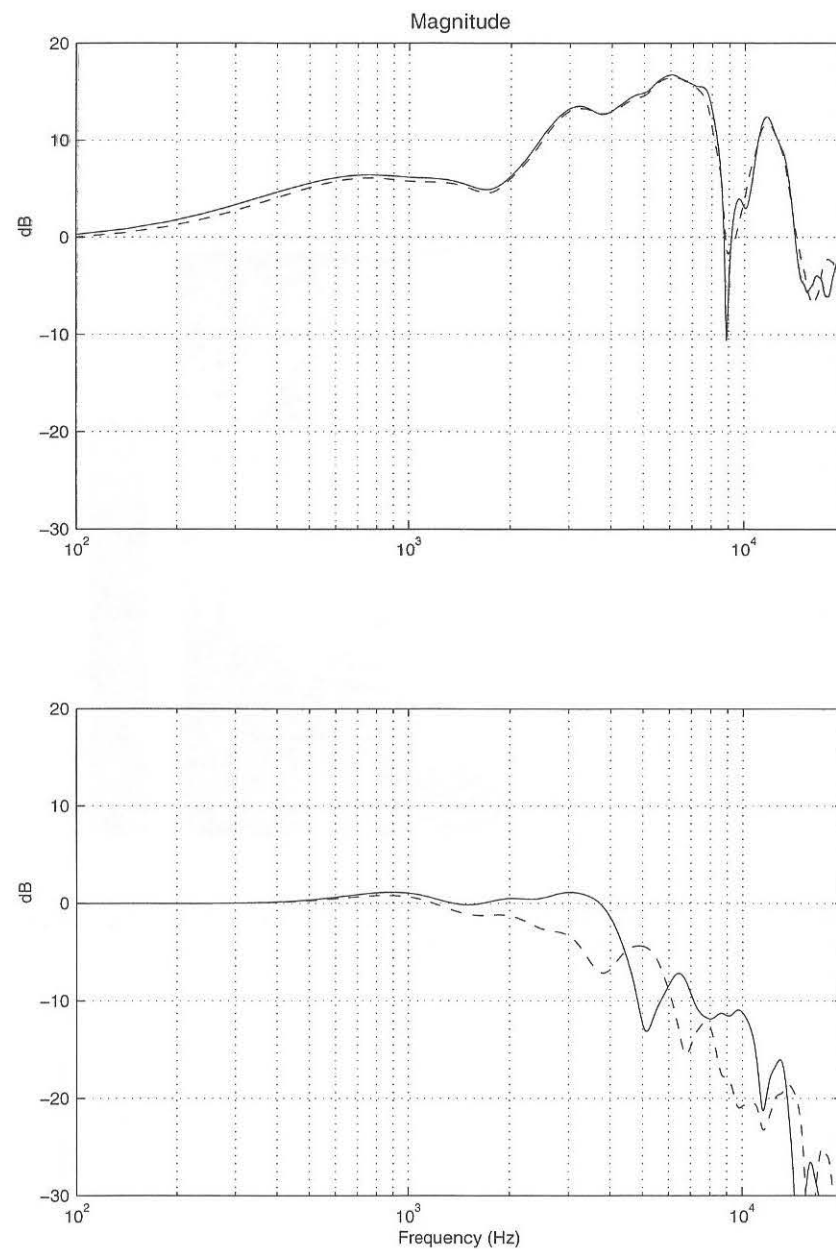


Figure 6. HRTFs measurements (solid line) and interpolations (dashed line) at 90 degrees (ipsilateral) and -90 degrees (contralateral) in the horizontal plane. Interpolations are made from measurements at 20 degrees resolution.